# Self-Similar Hot Accretion Flow onto a Neutron Star

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**Abstract.** We present analytical and numerical solutions which describe a hot, viscous, two-temperature accretion flow onto a neutron star or any other compact star with a surface. We assume Coulomb coupling between the protons and electrons, and free-free cooling from the electrons. Outside a thin boundary layer, where the accretion flow meets the star, we show that there is an extended settling region which is well-described by two self-similar solutions: (1) a two-temperature solution which is valid in an inner zone $r \leq 10^{2.5}$ ($r$ is in Schwarzchild units), and (2) a one-temperature solution at larger radii. In both zones, $\rho \propto r^{-2}$, $\Omega \propto r^{-3/2}$, $v \propto r^{0}$, $T_p \propto r^{-1}$; in the two-temperature zone, $T_e \propto r^{-1/2}$. The luminosity of the settling zone arises from the rotational energy of the star as the star is braked by viscosity; hence the luminosity is independent of $\dot{M}$. The settling solution is convectively and viscously stable and is unlikely to have strong winds or outflows. The flow is thermally unstable, but the instability may be stabilized by thermal conduction. The settling solution described here is not advection-dominated, and is thus different from the self-similar ADAF found around black holes. When the spin of the star is small enough, however, the present solution transforms smoothly to a (settling) ADAF.

## INTRODUCTION

At mass accretion rates less than a few per cent of the Eddington rate, black holes (BHs) and neutron stars (NSs) are believed to accrete via a hot, two-temperature, radiatively inefficient, quasi-spherical, advection-dominated accretion flow, or ADAF [1,2]. While the properties of BH ADAFs are quite well known, hot flows onto NSs have not been investigated. Their properties, such as the luminosity, spectra, torque applied to a central object, etc., are expected to be different from the BH ADAFs because a NS has a surface while a BH has an event horizon [2,3]. Here we discuss the structure of a hot accretion flow around a NS [4]. We do not attempt a detailed analysis of the boundary layer region near the NS surface.

## SELF-SIMILAR SETTLING SOLUTION

We consider a steady, rotating, axisymmetric, quasi-spherical, two-temperature accretion flow onto a star with a surface, and we use the height-integrated form of the viscous hydrodynamic equations. We assume the Shakura-Sunyaev-type viscosity parametrized by dimensionless $\alpha$. We assume viscous heating of protons, Bremsstrahlung cooling of electrons and Coulomb energy transfer from the protons to the electrons. We neglect thermal conductivity and Comptonization. In the inner zone $r < 10^{2.5}$ ($r$ is in Schwarzchild units, $R_S = 2GM/c^2$), the flow is two-temperature with the density, proton and electron temperatures, angular and radial velocities scalings as

$$\rho = \rho_0\, r^{-2}, \quad T_p = T_{p0}\, r^{-1}, \quad T_e = T_{e0}\, r^{-1/2}, \quad \Omega = \Omega_0\, r^{-3/2}, \quad v = v_0\, r^0, \qquad (1)$$

where $\rho_0,\ T_{p0},\ T_{e0}, \Omega_0, v_0$ are functions of $M,\ \alpha$ and the star spin $s = \Omega_*/\Omega_K(R_*)$, and $\Omega_K(R) = (GM/R^3)^{1/2}$ is the Keplerian angular velocity. In the outer zone $r > 10^{2.5}$, we have $T_e = T_p \propto r^{-1}$ and the same other scalings. This self-similar solution is valid for the part of the flow below the radius $r_s$ related to the mass accretion rate $\dot{m}$ (in Eddington units, $\dot{M}_{\rm Edd} = 1.4 \times 10^{18} m$ g/s, and here $m = M/M_\odot$):

$$\dot{m} < 2.2 \times 10^{-3} \alpha_{0.1}^2 s_{0.3}^2 r_{s,3}^{-1/2}, \qquad (2)$$

where $r_{s,3} = r_s/10^3$, $\alpha_{0.1} = \alpha/0.1$, etc.. The numerical solution of the hydrodynamic equations with appropriate inner and outer boundary conditions is represented in Figure 1. It is in excellent agreement with the self-similar solition (1).

## PROPERTIES OF THE SELF-SIMILAR SOLUTION

*Spin-Up/Spin-Down of the Neutron Star* — The angular momentum flux in the flow, $\dot{J}$, is negative which implies that the accretion flow removes angular momen-

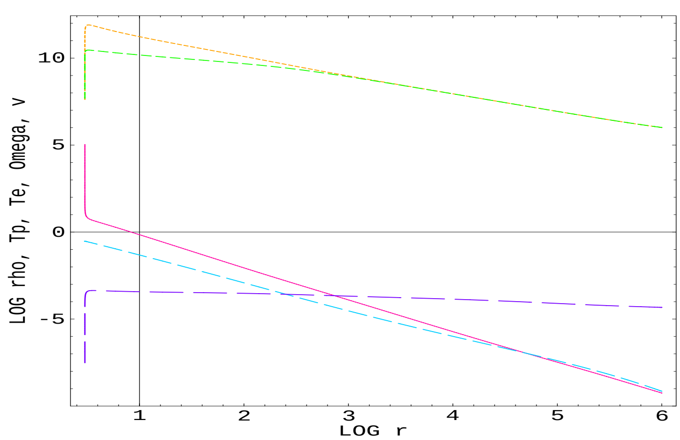


**FIGURE 1.** The radial profiles of density (*solid* curve), proton and electron temperatures (two *dotted* curves), angular velosity (*dashed* curve), and radial velosity (*long-dashed* curve).

tum from the star and spins it down. This behavior is quite different from that seen in thin disks [5,6], where for most choices of the stellar spin parameter $s$, the accretion disk spins up the star with a torque $\dot{J}_{\rm thin} \approx \dot{M}\Omega_K(R_*)R_*^2$. In contrast, for the self-similar solution derived here, the torque is negative for nearly all values of $s$. Moreover, $\dot{J}$ is independent of $\dot{M}$. Equivalently, the dimensionless torque, $j = \dot{J}/\dot{J}_{\rm thin}$, which is $\sim 1$ under most conditions for a thin disk, here takes on the value $j \simeq -43\dot{m}^{-1}\alpha^2 s^3 \left(1-s^2\right)^{3/2}$. This torque spins down the NS as $s = s_0/\sqrt{1+t/\tau}$, where the spin-down time is

$$\tau \simeq 2\times 10^8 s_{0.1}^{-2}\alpha_{0.1}^{-2}\left(R_m/R_*\right)^{-3/2} \text{ yr} \quad \text{or} \quad \dot{P}_*/P_*^2 \simeq 2.7\times 10^{-12} m_{1.4}^{-1}\alpha_{0.3}^2 s_{0.5}^3 \text{ s}^{-2}, \tag{3}$$

which is in excellent agrement with observational spin-down rates of some X-ray pulsars [7] (here $R_m$ is the magnetospheric radius). Note, the spin-down rate is independent of $\dot{M}$!

*Luminosity and Spectrum* — The total luminosity has two contributions: from the settling flow and from the boundary layer:

$$\begin{aligned} L_{SS} &\simeq 6.2\times 10^{34} m r_3^{-1}\dot{m}_{-2}s_{0.1}^2 + 8.9\times 10^{33} m r_3^{-1}\alpha_{0.1}^2 s_{0.1}^4 \text{ ergs/s}, \\ L_{BL} &\simeq 1.7\times 10^{36} m r_3^{-1}\dot{m}_{-2} \text{ ergs/s}. \end{aligned} \tag{4}$$

Note that for sufficiently low $\dot{m}$, the luminosity is independent of $\dot{m}$ and is dominated by the settling flow. Below the radius $r_c \sim 45\alpha_{0.1}^{1/2}s_{0.1}$ Comptonization is significant (although optical depth is always smaller than unity); therefore the self-similar solution (1) is not accurate. The observed spectrum from the settling flow (assuming free-free emission) is calculated to be:

$$\nu L_\nu \simeq 1.7\times 10^{31} m\alpha_{0.1}^2 s_{0.1}^4 \left(h\nu/[3 \text{ keV}]\right) \quad \text{ergs/s}. \tag{5}$$

which is sufficiently accurate up to $h\nu \sim kT_e(r_c) \sim 400\alpha_{0.1}^{-1/4}s_{0.1}^{-1/2}$ keV.

*Stability of the flow* — We demonstrate that the settling flow is convectively stable and may not have strong winds and outflows (the Bernoulli number is negative) if the adiabatic index satisfies

$$\gamma > (3/2)\left(1-s^2/2\right)/\left(1-s^2/4\right) \sim 1.5. \tag{6}$$

The flow is thermally unstable because it is cooling-dominated by free-free emission. Stabilization by thermal conduction is studied elsewhere.

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